

INTEGRATED OPTICAL DEVICE

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The present invention generally relates to the field of integrated optics, and particularly to integrated optical devices for Wavelength Division Multiplexing (WDM) optical communication systems. More specifically, the present invention relates to an integrated multiplexer/demultiplexer optical device, for dropping and/or adding optical signals from/to a wavelength division multiplexed optical signal (Optical Add-Drop Multiplexer - shortly OADM).

In WDM optical communications, a plurality of mutually independent optical signals are multiplexed in the optical wavelength domain and sent along a line, comprising optical fibers or integrated waveguides; the signals can be either digital or analogue, and they are distinguished from each other in that each of them has a specific wavelength, distinct from those of the other signals.

In the practice, specific wavelength bands of predetermined amplitude, also referred to as channels, are assigned to each of the signals at different wavelengths. The channels, each identified by a respective wavelength value called the channel central wavelength, have a certain spectral amplitude around the central wavelength value, which depends, in particular, on the characteristics of the signal source laser and on the modulation imparted thereto

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for associating an information content with the signal. Typical values of spectral separation between adjacent channels are 1.6 nm and 0.8 nm for the so-called Dense WDM (shortly, DWDM), and 20 nm for Coarse WDM (CWDM - ITU Recommendation No. G.694.2).

Currently, signal processing (multiplexing, demultiplexing, routing) is mainly performed on electrical signals, by means of electronic devices. Optical-electrical-optical conversion of the signals is therefore required. This constitutes the main bottleneck against the increase in the communication band.

Efforts are therefore being made for developing optical devices that are capable of processing the signals directly in the optical domain.

In particular, optical devices (optical demultiplexers), are required that are capable of separating the different channels of a wavelength division multiplexed optical signal travelling on a line, and routing the individual channels to the desired recipients. Similarly, optical devices (optical multiplexers) are necessary for receiving separate channels from distinct sources and combining them into a wavelength division multiplexed signal.

A known technique for realizing this kind of optical devices exploits Bragg filters, i.e., optical filters

obtained by means of Bragg gratings, essentially consisting of alternated regions of different refractive index; when an optical signal is propagated through the filter, some wavelengths are reflected, some others pass through the
5 filter, depending on the grating structure.

Integrated add/drop multiplexing devices are known comprising Bragg gratings realized in the arms of Mach-Zehnder interferometers. One such device is for example described in T. Erdogan et al., "Integrated-optical Mach-
10 Zehnder add-drop filter fabricated by a single UV-induced grating exposure", Applied Optics, Vol. 36, No. 30, 20 Oct. 1997, pages 7838-7845.

The Applicant observes that this device is a low refractive index contrast device.

15 The Applicant observes that these devices make use of low refractive index contrast Bragg gratings, i.e. gratings in which the difference in refractive index of the alternated regions is quite small. For the purposes of the present invention, with grating with a "low refractive index
20 contrast" it is intended a grating wherein the percentage difference $\Delta n = 100 \times (n_2/n_1 - 1)$ [%] between the refractive indexes n_1 and n_2 of the regions of different refractive index (n_1 being the lower value) is lower than 1.5%. Accordingly, in the following of the present description,
25 with "high refractive index contrast" it will be intended a

percentage difference greater of 1.5%.

The Applicant has observed that gratings having low refractive index contrast are adapted to reflect signals in a relatively small wavelength band, and are not particularly indicated for CWDM communications, where the width of each channel is relatively large. In addition to this, low refractive index contrast Bragg gratings have a significant length (the number of alternated regions must be high), which is in contrast with current trend towards high integration.

The Applicant has found that high refractive index contrast Bragg gratings should be preferred. Compared to low refractive index contrast Bragg filters, high refractive index contrast Bragg filters allow obtaining a wider band of reflected wavelengths and a higher reflectivity with a significantly lower number of pairs of alternated regions of different refractive indexes. High refractive index contrast Bragg filters can thus be made more compact than their low refractive index contrast counterparts.

US 4,790,614 discloses a one-chip monolithic multiplex wavelength transmission device. The device exploits a monolithic optical filter obtained by forming in an optical waveguide a plurality of gaps, arranged in the light propagation direction, having period and width equal to multiples of a quarter of wavelength of the propagating

signal, and a depth larger than the thickness of the waveguide. The gaps are filled with a material having a refractive index different from that of the waveguide. The optical filter is designed so as to reflect or transmit the
5 light thereon or therethrough depending on the wavelength characteristics thereof. Light-emitting semiconductor devices or photodetectors are formed monolithically on the light-transmitting and reflecting sides of the waveguide.

The Applicant has observed that using the technique
10 disclosed in that document, high refractive index contrast Bragg gratings can be formed. Two types of Bragg gratings are disclosed in that document: a first type of grating is adapted to create an optical filter having a relatively wide reflection band; a second grating type is intended to create
15 an optical filter having a relatively wide reflection band and, within the reflection band, a transmission band.

In particular, the Applicant has noted that this second type of gratings, intended to create optical filters capable of transmitting a selected range of wavelengths (pass band)
20 within a relatively wide stop band, actually cannot be practically exploited in the field of optical communications, due to the very poor pass band characteristics.

In addition to this, the Applicant has observed that
25 the different embodiments of multiplex device disclosed in

that document are affected by problems due to the fact that, in order to be able to separate and properly route different channels of a wavelength division multiplexed optical signal, the direction of propagation of the signal must be tilted with respect to a direction perpendicular to the grating axis (defined by a direction perpendicular to the interfaces between regions of different refractive indexes, i.e. the walls of the gaps forming the optical filter). In other words, the angle of incidence of the optical signal onto the grating that forms the optical filter must be different from zero.

In particular, the Applicant has found that this causes a worsening of the optical filter performance, reducing the effective bandwidth and reducing the slope of the transition between the reflective and the transmissive bands. Additionally, the transversal width of the reflected optical beam is widened, causing a loss of power in the reflected signal.

The Applicant has found that an integrated Mach-Zehnder comprising, on each of the coupled waveguides and in both coupling regions of the device, a grating that is formed by realizing gaps on the entire cross-section of the core of the waveguide and that has a percentage variation of the refractive index of at least 1.5%, is adapted to realize optical multiplexers/demultiplexers, particularly for the

use in WDM communications, and is not affected by the problems of the known devices. The grating structure may advantageously be realized with a still higher refractive index contrast, preferably higher than 10%, more preferably higher than 50%, which provides a spectral response more suitable for the here-considered WDM applications.

The proposed device is rather compact, allows separating different channels of a wavelength division multiplexed signal, and has an angle of incidence of the optical signals onto the optical filters that is equal to zero.

According to an aspect of the present invention, there is provided an integrated optical device as set forth in claim 1.

The integrated optical device of the present invention comprises a first and a second integrated waveguides, each comprising a core and a cladding, which are arranged so as to be in optical coupling relationship in a first and a second spaced-apart coupling regions, and which have respective optically uncoupled waveguide sections in between the first and second coupling regions.

A first and a second modulated refractive index structures are provided, each one formed along a respective uncoupled waveguide section and comprising at least one pair of regions having a first refractive index n_1 and,

respectively, a second refractive index n_2 greater than the first, said regions being adjacent to each other along the respective uncoupled waveguide section.

Said regions comprise a portion of the respective
5 uncoupled waveguide section and a gap formed in the uncoupled waveguide section, the percentage difference $\Delta n = 100 \times (n_2/n_1 - 1)$ [%] between said first and second refractive indexes being greater than 1.5%.

Preferably, the percentage difference is greater than
10 10 %, more preferably greater than 50%.

The gap extends at least across the entire cross-section of the core of the respective waveguide section.

An interface between the regions of mutually different refractive index is arranged orthogonally to the light
15 propagation direction in the respective uncoupled waveguide section. The problems inherent to tilted directions of incidence of the light onto the modulated refractive index structures are avoided.

The first and second modulated refractive index
20 structures may comprise each a plurality of pairs of regions of mutually different refractive index, arranged in succession along the respective uncoupled waveguide section.

In an embodiment of the invention, at least one of said plurality of pairs of regions is a transmissive pair,
25 adapted to transmitting optical signals with wavelengths

within a prescribed wavelength pass band; the remaining pairs of regions are instead reflective pairs, adapted to reflect optical signals with wavelengths within a prescribed wavelength stop band containing the pass band.

5 In particular, said pass band corresponds to at least one prescribed channel of a wavelength division multiplexed signal, and said stop band is at least as wide as an overall wavelength spectrum region occupied by the wavelength division multiplexed signal.

10 In a preferred embodiment, the at least one transmissive pair comprises two or more transmissive pairs, distributed among the reflective pairs. The Applicant has found that this allows achieving a relatively flat pass band.

15 All the transmissive pairs may have a same optical length in the light propagation direction, or they may have varying optical lengths in the light propagation direction. The Applicant has found that in order to achieve an even flatter pass band, in the first case a number of reflective
20 pairs between adjacent transmissive pairs preferably varies along the respective waveguide section; in the second case, the number of reflective pairs between adjacent transmissive pairs may be kept constant or be varied along the respective waveguide section.

25 According to preferred embodiments, the optical

coupling regions have optical coupling factors approximately equal to 50%, and the first and the second modulated refractive index structures are located along the respective uncoupled waveguide section in substantially identical
5 positions with respect to the first coupling region.

In particular, the first waveguide has a first input section, adjacent the first coupling region, and the second waveguide has a first and a second output sections, respectively adjacent the second and the first coupling
10 regions. An input wavelength division multiplexed optical signal, including a first optical signal with wavelength in said pass band and entering the device through said first input section is separated into a first output signal, corresponding to said first optical signal, and a second
15 output signal, corresponding to the input wavelength division multiplexed optical signal deprived of the first optical signal, the first and second output signals respectively exiting the device through the first and second output sections.

20 The first waveguide may further comprise a second input section, adjacent the second coupling region; a second optical signal with wavelength in said pass band and entering the device through said second input section propagates through the device to the second output section.

25 According to another aspect of the present invention,

there is provided an integrated optical add/drop device as set forth in claim 14. The integrated optical add/drop device is adapted to receiving an input wavelength division multiplexed optical signal including at least a first and a second optical signals differentiated by their wavelength bands, and selectively extracting the first and a second optical signals from the input wavelength division multiplexed optical signal. The device comprises at least a first and a second integrated optical devices according to the present invention, connected in cascade and having differentiated pass bands, corresponding to respective bands of the first and second optical signals.

In particular, the second output section of the first integrated optical device is coupled to the first input section of the second integrated optical device.

According to still another aspect of the present invention, there is provided a process for manufacturing an integrated optical device as set forth in claim 16.

In brief, the process comprises:

forming on a substrate at least a first and a second integrated waveguides, arranged so as to be in optical coupling relationship in a first and a second spaced-apart coupling regions with respective optically uncoupled waveguide sections in between the first and second coupling regions, and

forming along the optically uncoupled waveguide sections respective first and second modulated refractive index regions, comprising each at least one pair of regions of mutually different refractive index, adjacent to each other along the respective waveguide section.

The at least one pair of regions is formed by cutting away a portion of the respective waveguide section for defining a gap between two adjacent portions of the respective waveguide section; a refractive index of the gap is made different from a refractive index of the waveguide section of at least approximately 1.5 %.

In particular said cutting away is performed simultaneously in the optically uncoupled waveguide sections, for example using a mask defining a pattern of cuts to be formed in the optically uncoupled waveguide sections, and selectively removing the optically uncoupled waveguide sections according to the pattern defined by the mask.

The gaps may be filled with a substance having a refractive index different from that of the waveguide sections, such as air, or they may be vacuum emptied.

The features and advantages of the present invention will be made apparent by the following detailed description of some embodiments thereof, provided merely by way of non-limitative examples, which will be made referring to the

attached drawings, wherein:

FIG. 1 is a symbolic representation of a single-channel optical add/drop device;

FIG. 2 is a schematic view of the optical add/drop device of FIG. 1 realized according to an embodiment of the present invention;

FIG. 3 is a cross-sectional view along the plane III-III in FIG. 2;

FIG. 4 is a cross-sectional view along the plane IV-IV in FIG. 2, showing a portion of one of a pair of Bragg gratings formed in the device of FIG. 2;

FIG. 5 schematically shows, in cross-sectional view similar to that of FIG. 4, a complete Bragg grating structure according to an embodiment of the present invention;

FIG. 6 shows in diagrammatic form an optical response of the Bragg grating of FIG. 5;

FIGS. 7 and 8 schematically show, respectively in top plan view and in cross-section along the plane VIII-VIII, the device of FIG. 2 at an intermediate step of a manufacturing process according to an embodiment of the present invention;

FIG. 9 schematically shows the operation of the optical add/drop device of FIG. 2;

FIG. 10 is a symbolic representation of a four-channel

optical add-drop device; and

FIG. 11 is a schematic view of the four-channel optical add/drop device realized according to an embodiment of the present invention.

5 With reference to the drawings, and particularly to **FIG. 1**, a single-channel optical add/drop device **101** is a four-port device with two input ports **IP1** and **IP2** and two output ports **OP1** and **OP2**. A first input port **IP1** receives a wavelength division multiplexed optical signal $S_{\text{IN}}\{S(\lambda_1),$
10 $S(\lambda_2), \dots\}$ made up of a plurality (two or more) of optical signals $S(\lambda_1), S(\lambda_2), \dots$. Each of the signals $S(\lambda_1), S(\lambda_2), \dots$ is assigned a respective wavelength band (also referred to as a channel) centered on a respective wavelength $\lambda_1, \lambda_2, \dots$ (also referred to as the channel central wavelength). For
15 example, considering the case of a four-channel CWDM transmission, the channel central wavelengths are 1470 nm, 1490 nm, 1510 nm and 1530 nm.

One of the signals, namely the signal $S(\lambda_1)$ in the shown example (with, e.g., $\lambda_1 = 1490$ nm), is extracted
20 (dropped) from the multiplexed optical signal $S_{\text{IN}}\{S(\lambda_1), S(\lambda_2), \dots\}$ and made available at a first output port **OP1** of the add/drop device **101**; the dropped signal $S(\lambda_1)$ can thus be routed to the prescribed recipient, for example a user home appliance such as a television set, a telephone set, a
25 personal computer and the like, wherein the optical signal

is transformed into a corresponding electrical signal by means of a photodetector (not shown). A second input port IP2 of the add/drop device 101 is adapted to receive an optical signal $S'(\lambda_1)$, generated for example by a user home appliance laser source and centered on the same wavelength λ_1 as the dropped signal $S(\lambda_1)$; the signal $S'(\lambda_1)$ is added to the remaining signals $S(\lambda_2), \dots$, and a new multiplexed signal $S_{\text{out}}(S'(\lambda_1), S(\lambda_2), \dots)$, resulting from the combination of the original signals $S(\lambda_2), \dots$ not dropped, and the added signal $S'(\lambda_1)$, is made available at a second output port OP2 of the add/drop device 101.

FIG. 2 schematically shows the single-channel add/drop device 101 realized according to an embodiment of the present invention. The device includes a Mach-Zehnder Interferometer, hereinafter shortly referred to as MZI. The MZI comprises a first optical waveguide 201 and a second optical waveguide 203, arranged so as to be in optical coupling relationship in spaced-apart first and a second optical coupling regions 205 and 207, wherein the two optical waveguides 201 and 203 are in close proximity to each other. Each optical coupling region 205 and 207 forms a directional coupler, particularly a 50/50 (also referred to as 3 dB) optical coupler: a predetermined fraction, particularly a half, of the optical power propagating along either one of the two waveguides 201 and 203 is transferred

to the other waveguide. Respective sections 209 and 211 of the two optical waveguides 201 and 203 located between the first and the second optical coupling regions 205 and 207, and sufficiently spaced apart from each other so as to be
5 optically uncoupled, form the interferometer arms. The MZI can thus be seen as formed by two directional optical couplers, joined to each other by two optical waveguide sections (the interferometer arms).

An end 213 of the first waveguide 201, adjacent the
10 first coupling region 205, forms the first input port IP1 of the add/drop device; an opposite end 215 of the first waveguide, adjacent the second coupling region 207, forms the second input port IP2. A first end 217 of the second waveguide 203, adjacent the second coupling region 207,
15 forms the first output port OP1 of the add/drop device; an opposite end 219 of the second waveguide, adjacent the first coupling region 205, forms the second output port OP2.

In accordance with an embodiment of the present invention, the MZI is a monolithic device, integrated in a
20 chip schematically shown in FIG. 2 and denoted therein by 221, and the optical waveguides 201 and 203 are integrated planar waveguides; in particular, the waveguides 201 and 203 may be buried waveguides, ridge waveguides or raised strip waveguides. FIG. 3 shows a schematic cross-sectional view of
25 the MZI along the plane III-III, in the exemplary case of

the waveguides 201 and 203 being buried waveguides, particularly silica buried waveguides. The structure comprises a substrate 301, for example of a semiconductor material such as silicon. Alternatively, the substrate 301
5 can be made of a dielectric material, a magnetic material or glass.

A lower cladding layer 303 is formed on the substrate 301. The lower cladding layer 303 is for example made of silica. The cores of the waveguides 201 and 203 are formed
10 by strips of a layer 305 of doped silica; the strips of doped silica layer 305 are immersed in a first upper cladding layer 307 made for example of silica. The first upper cladding layer 307 is covered by a second upper cladding layer 309, of the same material as the first upper
15 cladding layer. Optical signals are guided by the waveguide cores because of the difference in the refractive indexes of the doped silica layer 305, having in particular a higher refractive index, and the lower and the first upper cladding layer 303 and 307, having a lower refractive index. Given a
20 refractive index contrast between the waveguide cores and the cladding layers, the dimensions of the waveguide cores are chosen in such a way to have single-mode waveguides; the thickness of the cladding layers are chosen to reduce the losses, and in particular the thickness of the lower
25 cladding layer is such as to decouple the propagating mode

from the substrate.

Referring back to FIG. 2, along each of the two interferometer arms 205 and 207, a respective Bragg grating 223 and 225 is formed. The Bragg gratings 223 and 225 are designed to have an optical response such that a signal in the channel band centered on a prescribed wavelength, particularly the wavelength λ_1 (for example, 1490 nm) can be separated from the signals in the other channel bands, centered on the wavelengths λ_2, \dots (e.g., 1470 nm, 1510 nm and 1530 nm).

In particular, as visible in FIG. 4, the Bragg gratings 223 and 225 are formed by providing a longitudinal succession of trenches or gaps 401 along each section 205 and 207 of the waveguides 201 and 203, in the direction of propagation of the optical signals. The gaps 401 extend from the top surface of the first upper cladding layer 307 down through the doped silica layer 305 and partially into the lower cladding layer 303. Each Bragg grating 223, 225 thus comprises gaps 401 alternated to portions 403 of the waveguide core. The gaps 401 may be filled with a fluid, such as air, gas or a liquid, or with other materials, such as glasses or oxides having a desired refractive index, or they may be emptied to create vacuum thereinside. The second upper cladding layer 309 seals the top free open side of the gaps 401.

The alternation of gaps 401 and portions 403 of the waveguide core forms a structure having a modulated refractive index, capable of performing a filtering in the wavelength domain.

5 A gap 401 followed, in the propagation direction of the optical signals, by an adjacent waveguide portion, comprised of a portion 403 of the waveguide core and the associated portions of the lower and upper cladding, form an elemental unit of the modulated refractive index structure, and
10 particularly an elemental unit of the Bragg gratings; such an elemental unit will be hereinafter referred to as a cell; in FIG. 4 only two cells C of the Bragg grating 225 are shown, for simplicity.

A cell has a spectral response determined by the
15 overall dimension of the cell in the light propagation direction ($d_1 + d_2$ in FIG. 4), and by the ratio between the dimensions d_1 and d_2 (taking account of the respective refractive indexes).

Let n_1 and n_2 be the refractive indexes of the two
20 regions of the cell, namely the gap 401 and the adjacent waveguide portion 402; it is intended that n_1 and n_2 are the effective indexes for the propagating mode.

Assuming that the difference between n_1 and n_2 is small (as in low refractive index contrast structures), it can be
25 shown that a cell is transmissive (i.e., a propagating mode

of wavelength λ passes through the cell) if

$$(n_1 d_1 + n_2 d_2) = m(\lambda/2) + \lambda/4$$

while the cell is reflective (the propagating mode is reflected) if

5
$$(n_1 d_1 + n_2 d_2) = m(\lambda/2)$$

where m is a positive integer, commonly referred to as the order of the cell.

Once the dimension d_1 is chosen, these two equations allow determining the dimension d_2 so that the cell is
10 transmissive or reflective:

$$\text{transmissive cell: } d_2 = (2m + 1)(\lambda/4n_2) - d_1(n_1/n_2)$$

$$\text{reflective cell: } d_2 = m(\lambda/2n_2) - d_1(n_1/n_2).$$

The Applicant has however observed that these formulas are the result of an approximation, based on the assumption
15 that the refractive index contrast is low. These formulas cannot be applied in the case the difference between n_1 and n_2 is not small, as in high refractive index contrast structures. The Applicant has therefore derived exact conditions that are valid also in the case the difference
20 between n_1 and n_2 is high. In particular, the conditions under which a cell is transmissive are:

$$d_1 = m(\lambda/2n_1) \tag{1}$$

or

$$d_2 = (\lambda/2\pi n_1) (m\pi + \alpha) \tag{2}$$

25 where α is a correction factor given by:

$$\alpha = \arctan \{ [(1 - \rho^2) \cos \phi_2] / [(1 + \rho^2) \cos \phi_2] \};$$

ρ is the field reflectivity at the interface between the two regions of different refractive indexes of the cell, and ϕ_2 is the phase contribution due to the propagation within the region of dimension d_2 of the cell.

It can be appreciated that if d_1 is chosen to be equal to an integer multiple of half a wavelength of the propagating mode (equation (1)), the cell result to be transmissive irrespective of the value of d_2 . For values of d_1 different from an integer multiple of half a wavelength of the propagating mode, the cell result to be transmissive only if d_2 is chosen according to the equation (2), while the cell result to be reflective if d_2 is chosen according to the following equation:

$$d_2 = (\lambda / 2\pi n_1) [(m - \frac{1}{2})\pi + \alpha] \quad (3).$$

Using a high refractive index contrast Bragg grating, and properly dimensioning the cells so as to result reflective at a desired wavelength, it is possible to obtain an optical filter adapted to reflect optical signals with wavelengths within a prescribed, relatively wide band (reflection band or stop band) centered on the desired wavelength. A relatively small number of reflective cells is sufficient for achieving a relatively wide stop band and an approximately 100% reflectivity within such a band. On the contrary, this result cannot be achieved using low

refractive index contrast Bragg gratings, because even for large number of reflective cells the width of the stop band would be very limited, and the reflectivity within such a band would not reach 100%.

- 5 Defining the refractive index contrast between the two regions of a cell as $\Delta n = 100 \times (n_2/n_1 - 1)$ [%], for the purposes of the present invention a high refractive index contrast means $\Delta n > 1.5$ %.

10 In the present case, if the filler of the gaps 401 is chosen in such a way to have a refractive index significantly different from that of the doped silica layer 305, a high refractive index contrast Bragg filter can be obtained. A typical refractive index value of a waveguide core made of doped silica is approximately 1.45 at a
15 wavelength of approximately 1500 nm, while a gap 401 filled with air has a refractive index approximately equal to 1 at that wavelength; the refractive index contrast is thus equal to approximately 45%, i.e., the Bragg grating thus obtained forms a filter having a high refractive index contrast.
20 Other materials can of course be used to fill the gaps 401, which still allow obtaining a high refractive index contrast structure.

If, among a plurality of cells reflective at the desired stop band central wavelength, at least one cell is
25 placed that is dimensioned to be transmissive at a desired

pass band central wavelength within the stop band, it is possible to obtain an optical filter adapted to reflect optical signals with wavelengths within the stop band, at the same time capable of transmitting optical signals with
5 wavelengths within a prescribed, relatively narrow pass band centered on the pass band central wavelength.

In particular, the stop band may be chosen to extend through the whole spectral region occupied by a wavelength division multiplexed signal having a prescribed number of
10 channels, and the pass band may be chosen to correspond to one or more of the channels of the wavelength division multiplexed signal, with the pass band central wavelength substantially coincident with the respective channel central wavelength.

15 Although in principle just one transmissive cell, properly dimensioned and inserted among the plurality of reflective cells, is sufficient to create a pass band within the stop band, the Applicant has observed that the lorentzian shape of the resulting pass band is not suitable
20 for practical applications in the field of optical communications, due to the narrowness of the pass band at high transmittivity values, and its slow extinction. The Applicant has observed that a larger and flatter pass band, with faster extinction rate out of the desired wavelength
25 range can be obtained by providing more than just one

transmissive cell, distributed among the reflective cells.

In addition, the Applicant has found that even better results in terms of pass band flatness are obtained if the number of reflective cells placed among the transmissive cells, and/or the dimensions of the transmissive cells are properly chosen.

For example, referring to FIG. 5, there is schematically shown, in cross-sectional view similar to that of FIG. 4, a Bragg grating structure according to an embodiment of the present invention (also referred to as an apodized Bragg grating structure). The grating comprises sixteen trenches or gaps 401, defining fifteen cells C1 - C15. The dimensions of the cells C1 - C15 are such that some cells, particularly the cells C2, C3, C5, C6, C7, C9, C10, C11, C13 and C14 (denoted as R in the drawing) are reflective at the wavelength λ_{SB} (FIG. 6), while some other cells, particularly the cells C1, C4, C8, C12 and C15 (denoted as TX) are transmissive at the wavelength $\lambda_{\text{TB}} = \lambda_1$.

In the shown embodiment, the different spectral behaviour of the reflective and transmissive cells is achieved by acting (varying) the dimension of the portions 403 of waveguide core in the cells, while the dimension of the gaps 401 is kept constant and equal to d1. In particular, given the dimension d1, the dimensions of the portions 403 of waveguide core in the cells are determined

on the basis of the equations (1), (2) and (3) reported previously. In the shown example, the dimension of the portion 403 of waveguide core in all the reflective cells C2, C3, C5, C6, C7, C9, C10, C11, C13 and C14 is set equal to d21, and the dimensions of the portion 403 of waveguide core in the transmissive cells C1, C4, C8, C12 and C15 are chosen in such a way that the dimension of the portion 403 of waveguide core in the first and the fifth transmissive cells C1 and C15 has a first value d22, the dimension of the portion 403 of waveguide core in the second and the fourth transmissive cells C2 and C12 has a second value d23 lower than the first value d22, and the dimension of the portion 403 of waveguide core in the third transmissive cell C8 has a third value d24 higher than the first value d22.

15 In the exemplary Bragg grating shown FIG. 5, not only are the dimensions of the transmissive cells varied in the light propagation direction, but also the number of reflective cells between adjacent transmissive cells varies. In particular, two reflective cells are placed between the first two transmissive cells, three reflective cells are placed between the second two transmissive cells and between the third two transmissive cells, and two reflective cells are placed between the last two transmissive cells.

25 More generally, it can be observed that a transmissive cell constitutes a sort of defect in a regular structure

comprising only reflective cells; such a defect, together with the adjacent reflective cells, acts like a Fabry-Perot resonant cavity with mirrors represented by the reflective cells adjacent the transmissive cells; the light stays in
5 such a cavity for a time related to the cavity length (i.e., the dimension of the transmissive cell) and the mirror reflectivity related to the number of adjacent reflective cells. In order to have a flat pass band, the dimensions of the transmissive cells and the distribution of reflective
10 cells among the transmissive cells shall be such that the distribution of the times of permanence of the light in the cavities is substantially gaussian, with a maximum located substantially at the center of the whole structure. This can be achieved by varying the number of reflective cells
15 (keeping the dimensions and the number of the transmissive cells fixed), so that the reflective cells increase in number in the first half of the grating (adjacent to the first optical coupler 205), while they decrease in number in the second half of the grating (adjacent the second optical
20 coupler 207); in particular, the distribution of reflective cells in the second half of the grating can be generically symmetric to the distribution of reflective cells in the first half of the grating. Alternatively, the number of reflective cells between adjacent transmissive cells can be
25 kept constant, and the dimensions of the transmissive cells

be increased towards the center of the grating. In still another alternative, both the transmissive cell dimensions and the number of reflective cells between adjacent transmissive cells can be varied as described above.

5 In the example of FIG. 5, the number of reflective cells increases towards the centre of the grating, while the dimension of the transmissive cells first decreases and then increases.

Based on the previous considerations, Bragg gratings
10 223, 225 can be formed constituting band-pass filters having a stop band (SB in FIG. 6) spanning the wavelength range of the wavelength division multiplexed signal, and a pass band (PB1 or PB2 in FIG. 6) corresponding to one of the channels of the wavelength division multiplexed signal. Optical
15 signals with wavelengths falling within the pass band can pass through the grating substantially unattenuated, while optical signals with wavelengths falling within the stop band are reflected. For example, FIG. 6 schematically shows the optical response of Bragg gratings adapted to be used in
20 the context of CWDM optical communications, designed to have a stop band SB of approximately 90 nm centered on a central stop band wavelength λ_{SB} of approximately 1490 nm, and a pass band PB1 or PB2 (of approximately 20 nm) centered on a desired pass band central wavelength λ_1 or λ_2 (1490 or 1470
25 nm).

The Applicant designed an integrated optical device of the type shown in FIG. 2. The thickness of the silica layer forming the lower cladding layer 303 was in the range 10 - 20 μm ; the thickness and width of the doped silica layer forming the waveguide cores 305 was approximately 4 - 5 μm ; the thickness of the silica layer forming the first upper cladding layer 307 was approximately 10 μm ; and the thickness of the silica layer forming the second upper cladding layer 309 was approximately 10 μm . The waveguide cores had a refractive index of 1.454, and the cladding layers had a refractive index of 1.444. The gaps 401 were filled with air. Bragg gratings having each an overall length of 68.39 μm were formed in the interferometer arms, with gaps 401 of 500 nm; the length of the waveguide core 305 sections in the reflective cells was 1.714 μm , the length of the waveguide core sections in the transmissive cells C1 and C15 was 8.648 μm , the length of the waveguide core sections in the transmissive cells C4 and C12 was 7.621 μm , and the length of the waveguide core sections in the transmissive cell C8 was 10.702 μm . Experiments conducted on such a grating structure evidenced that the grating provided a quite flat pass band centered on a wavelength of 1490 nm, with rather steep edges. These Bragg gratings are suitable for separating the channel λ_1 , centered on 1490 nm, from the remaining channels of a coarse wavelength division

multiplexed signal.

A process for the manufacturing of an add/drop device according to an embodiment of the present invention will be now described. In particular, the process that will be
5 described by way of example refers to the manufacturing of a device in silica buried waveguide technology.

Firstly, the silica layer 303 that will form the lower cladding layer is formed on the silicon substrate 301; in particular, the layer 303 can be formed by deposition, by
10 means of conventional deposition techniques such as the Chemical Vapour Deposition (CVD), the Flame Hydrolysis Deposition (FHD) or the electron-beam deposition.

Then, the doped silica layer 305 is formed on the lower cladding layer 303, for example by means of any one of the
15 cited deposition techniques. The doping of the layer is achieved by introducing into the reaction chamber the desired dopants; for example, a germanium-doped silica layer can be obtained by mixing SiCl_4 and GeCl_4 .

The doped silica layer 305 must then be patterned to
20 define the two waveguide cores 201 and 203. This can be achieved by means of photolithographical techniques: a layer of a photosensible resin (photoresist) is deposited on the layer 305, and the photoresist layer is then selectively exposed to radiation (typically, UV light) through a
25 suitable mask. The areas of the photoresist that have been

exposed to the radiation are then removed. By means of an etching process, uncovered areas of the doped silica layer 305 are then removed, to define the waveguide cores; the etching process is preferably anisotropic (e.g., Reactive Ion Etching - RIE). After the etching, the photoresist is completely removed.

The first upper cladding layer 307 is then formed on the structure, for example by means of any of the cited deposition techniques.

10 In this way, a structure including the two buried waveguides 201 and 203 is obtained.

The two Bragg gratings are then formed along the two sections 209, 211 of the waveguides forming the interferometer arms. Similarly to the definition of the waveguide cores, this is achieved by means of photolithographic techniques. A mask layer is first deposited on top of the first upper cladding layer 307. FIGS. 7 and 8 schematically show, respectively in top-plan view and in cross-section along one of the interferometer arms, a portion of the device with the mask layer applied. Reference numeral 701 denotes the mask layer. It can be seen that generically rectangular windows 703 are formed in the mask layer 701, said windows extending transversally to the interferometer arms. A following etching process allows removing the first upper cladding layer 307, the doped

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silica layer 305 forming the two waveguide cores and part of the lower cladding layer 303 in correspondence of the rectangular gaps in the mask layer 701. In this way, the gaps 401 schematically shown in FIG. 4 are formed. In particular, the gaps 401 preferably have a depth that depends on the mode-field diameter (MFD) of the optical signals; preferably, the depth of the gaps is at least equal to twice the MFD: the Applicant has found that in this way the transmittivity is not significantly affected. The etching process is anisotropic, due to the relatively small aspect ratio of the gaps 401 to be formed.

After this step, the mask layer 701 is removed, and the second upper cladding layer 309 is formed on top of the structure, so as to seal the gaps 401.

It is observed that by means of the process described, the two Bragg gratings are formed simultaneously and can easily be made identical to each other, as well as located substantially at a same longitudinal position along the two interferometer arms.

The Applicant has realized an add/drop device of the type shown in FIG. 2 in silica buried waveguide technology. The two waveguides 201 and 203 were spaced apart of approximately 5 μm in the regions of the optical couplers 205 and 207, which had both a length of approximately 1221 μm . The distance between the waveguides in the region of the

interferometer arms was approximately 25 μm . The rectilinear sections of the waveguides were joined together by sinusoidally bent waveguide sections.

The operation of the add/drop device shown in FIG. 2 will be now explained making reference to the schematic view of FIG. 9. Concerning the drop operation, when the multiplexed signal $S_{\text{IN}}\{S(\lambda_1), S(\lambda_2), \dots\}$, entering the device from the first input port IP1 and propagating through the first waveguide 201, reaches the first coupler 205, a half of the optical power is transferred to the second waveguide 203; as a consequence, two half-power multiplexed signals, indicated in the drawing as $\frac{1}{2}[S_{\text{IN}}\{S(\lambda_1), S(\lambda_2), \dots\}]$, propagate through the first and the second waveguides 201 and 203, the half-power multiplexed signal propagating through the second waveguide 203 being in phase quadrature ($\pi/2$ phase shift) compared to the half-power multiplexed signal propagating through the first waveguide 201. When the two half-power signals $\frac{1}{2}[S_{\text{IN}}\{S(\lambda_1), S(\lambda_2), \dots\}]$ reach the Bragg gratings 223, 225 formed in the respective interferometer arm, only the half-power signals $\frac{1}{2}[S(\lambda_1)]$ in the wavelength band centered on the wavelength λ_1 are transmitted, the remaining half-power multiplexed signals (indicated in the drawing by $\frac{1}{2}[S_{\text{IN}}\{S(\lambda_2), \dots\}]$) being reflected. When the two half-power signals $\frac{1}{2}[S(\lambda_1)]$ reach the second optical coupler 207, an additional $\pi/2$ phase shift causes the full optical power

signal $S(\lambda_1)$ to be made available at the first output port OP1 of the device. For a similar reason, the reflected half-power signals $\frac{1}{2}[S_{IN}(S(\lambda_2),...)]$ constructively recombine when they pass back through the first optical coupler 205, and a full power multiplexed signal $S_{IN}(S(\lambda_2),...)$ is available at the second output port OP2 of the device.

The device also allows adding a new signal $S'(\lambda_1)$, centered on the same wavelength λ_1 as the dropped signal $S(\lambda_1)$, to the full power multiplexed signal $S_{IN}(S(\lambda_2),...)$, thereby obtaining the multiplexed output signal $S_{OUT}(S'(\lambda_1), S(\lambda_2),...)$. If the new signal $S'(\lambda_1)$ is fed to the second input port IP2 of the device and propagated through the first waveguide 201, when such a signal reaches the second optical coupler 207 a half of the optical power is transferred to the second waveguide 203; as a consequence, two half-power signals $\frac{1}{2}[S'(\lambda_1)]$, in phase quadrature, propagate through the first and the second waveguides 201 and 203. These half-power signals $\frac{1}{2}[S'(\lambda_1)]$ are transmitted by the Bragg grating 223 and 225 formed in the respective interferometer arm. When the signals reaches the first optical coupler 205, they recombine constructively in the second waveguide 203 and a full-power signal $S'(\lambda_1)$ is made available at the second output port OP2 of the device. This signal, together with the multiplexed signal $S_{IN}(S(\lambda_2),...)$, forms the multiplexed output signal $S_{OUT}(S'(\lambda_1), S(\lambda_2),...)$.

It can be appreciated that in the described device, because of the substantial orthogonality between gaps 401 and waveguides 201 and 203, the angle of incidence of the optical signals onto the gratings is substantially equal to
5 zero.

It is observed that in order to achieve the desired performance, neither the length of the two interferometer arms 209 and 211, nor the longitudinal position of the Bragg gratings 223 and 225 along the interferometer arms are
10 critical to the device design. However, it is important that the MZI be balanced, i.e., that the two interferometer arms have the same length, and that the two Bragg gratings be identical and identically located longitudinally along the two interferometer arms. The manufacturing process described
15 in the foregoing assures that these conditions are satisfied.

The use of monolithic Bragg grating structures formed by means of relatively deep trenches allows obtaining a high refractive index contrast; these gratings allow achieving
20 satisfactory performances in terms of stop band and pass band with gratings of very small length. Also, manufacturing processes can be devised such that the gratings are identical to each other and identically located along the interferometer arms of the MZI.

25 By combining a plurality of single-channel add/drop

devices of the type shown in FIG. 2, a multi-channel add/drop device can be obtained. For example, FIG. 10 is a symbolic representation of a four-channel add/drop device; the device comprises an input port IP1 adapted to receiving a four-channel wavelength division multiplexed signal $S_{IN}\{S(\lambda_1), S(\lambda_2), S(\lambda_3), S(\lambda_4)\}$, four output ports (drop ports) OP11 to OP14, each one delivering a respective one of the four signals $S(\lambda_1), S(\lambda_2), S(\lambda_3), S(\lambda_4)$ composing the four-channel signal $S_{IN}\{S(\lambda_1), S(\lambda_2), S(\lambda_3), S(\lambda_4)\}$, four input ports (add ports) IP21 to IP24, each one adapted to receiving a respective new signal $S'(\lambda_1), S'(\lambda_2), S'(\lambda_3), S'(\lambda_4)$ centered on a prescribed one of the four wavelengths $\lambda_1, \lambda_2, \lambda_3, \lambda_4$; and an output port OP2 delivering a new four-channel wavelength division multiplexed signal $S_{OUT}\{S'(\lambda_1), S'(\lambda_2), S'(\lambda_3), S'(\lambda_4)\}$ resulting from the combination of the four signals $S'(\lambda_1), S'(\lambda_2), S'(\lambda_3), S'(\lambda_4)$.

FIG. 11 schematically shows a four-channel add/drop device realized according to an embodiment of the present invention. The device comprises four single-channel add/drop devices 1011, 1012, 1013, 1014 of the type shown in FIG. 2, connected in cascade to each other. A first add/drop device 1011 receives the original four-channel multiplexed signal $S_{IN}\{S(\lambda_1), S(\lambda_2), S(\lambda_3), S(\lambda_4)\}$, drops therefrom the signal $S(\lambda_1)$, and adds thereto the signal $S'(\lambda_1)$, delivering a

four-channel multiplexed signal $S\{S'(\lambda_1), S(\lambda_2), S(\lambda_3), S(\lambda_4)\}$ to a second add/drop device 1012; the second add/drop device 1012 drops from the multiplexed signal $S\{S'(\lambda_1), S(\lambda_2), S(\lambda_3), S(\lambda_4)\}$ the signal $S(\lambda_2)$ and adds thereto the signal $S'(\lambda_2)$, delivering a four-channel multiplexed signal $S\{S'(\lambda_1), S'(\lambda_2), S(\lambda_3), S(\lambda_4)\}$ to a third add/drop device 1013; the third add/drop device 1013 drops from the multiplexed signal $S\{S'(\lambda_1), S'(\lambda_2), S(\lambda_3), S(\lambda_4)\}$ the signal $S(\lambda_3)$ and adds the signal $S'(\lambda_3)$, delivering a new four-channel multiplexed signal $S\{S'(\lambda_1), S'(\lambda_2), S'(\lambda_3), S(\lambda_4)\}$ to a fourth add/drop device 1014; finally, the fourth add/drop device 1014 drops the signal $S(\lambda_4)$ from the multiplexed signal $S\{S'(\lambda_1), S'(\lambda_2), S'(\lambda_3), S(\lambda_4)\}$ and adds thereto the signal $S'(\lambda_4)$, thereby delivering at the output port OP2 of the device the output four-channel multiplexed signal $S_{out}\{S'(\lambda_1), S'(\lambda_2), S'(\lambda_3), S'(\lambda_4)\}$.

More complex structures can easily be obtained by cascading more single-channel add/drop devices. For example, Bragg gratings having different optical response may be used, e.g. gratings that are reflective for two or more channels and transmissive for two or more adjacent channels in the wavelength division multiplexed signal.

Although the present invention has been disclosed and described by way of some embodiments, it is apparent to those skilled in the art that several modifications to the

described embodiments, as well as other embodiments of the present invention are possible without departing from the scope thereof as defined in the appended claims.